In-swarm: using 6G in-X subnetworks for controlling a swarm of UAVs

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***Abstract*—The importance of tactical communication in modern warfare is significant. Nowadays tactical communication is much more than just issuing orders and sharing intelligence. Also, the nature of tactical communication is far different than typical civilian communications. New and existing threats such as electronic warfare put a lot of pressure on wireless tactical communication development. The 6th generation (6G) radio access technology is expected to bring support for extreme communication utilizing in-X subnetworks. These short-range low power subnetworks are characterized by low latency, high throughput and reliability. Nevertheless, due to primarily to their short range, their use in tactical communications is limited. However, this paper recognizes that with some modifications the subnetworks could be utilized in controlling UAV swarms. A high level concept of in-swarm subnetwork and its tactical use cases are presented. Still, many open research issues and challenges are apparent and presented.**

I. Introduction

Communications are vital in modern warfare. Also, nowadays tactical communications encompass much more than just issuing orders or sharing intelligence. For example, unmanned aerial vehicles (UAVs) play a major role in todays conflicts [1]. To operate UAVs reliable and low latency wireless communications are needed. Additionally, the tactical communication environment can differ greatly from modern life. Tactical communication often relies more on ad hoc types of networks as communication infrastructure is critical and high priority target for adversaries. Further, electronic warfare (EW) actions such as blocking, intercepting and interfering with the communications or the spectrum, pose significant threats to wireless communications in conflict environments. Thus, tactical wireless communications should be as covert as possible and robust against interference and jamming.

Research on the 6h Generation (6G) radio technology has already started and attractive visions have been brought forward in industry and academia [2]. One such vision is the 6G in-X subnetwork concept presented in [3], where the X is the entity in which the subnetwork is located. The 6G in-X subnetwork concept aims to be a wireless alternative to many wired solutions of today by taking advantage of the support for extreme communication requirements in terms of throughput , latency and reliability in 6G, that is possible due to capillary wireless coverage. For example, the possible civil use cases for 6G in-X subnetworks have been presented: in-Vehicle/Body/Robot/House subnetworks, where latency, reliability, and/or throughput requirements are stringent [4] [3].

On one hand, the 6G in-X subnetwork concept assesses relevant topics relating to tactical communication. The in-X subnetworks are designed to be low power, thus covert, and resistant to interference/jamming. Also, in-X subnetwork ability to operate both independendtly and as a part of larger network is crucial, because the operation of the subnetworks will not halter when they are not connected to a larger network.

On the other hand, some of the presented civil usecases, where wireless solutions replace wired ones, have limited effect in military equipment. More specifically, many of supposed listed benefits of 6G in-X subnetworks brought forward, for example, in [3] have minimal use in tactical applications. For example, the weight reduction from removing cabling in military equipment is insignificant as large majority of the equipment is armored, and thus already heavy. More, the armor and other metal/thick parts of military equipment might negatively alter the signal environment of the bandwidths used by 6G in-X subnetworks. Also, the short range of 6G in-X subnetworks limits numerous applications e.g. tactical communication bubbles [5]. Further, the support of extreme communication requirements might not be decisive in tactical communications. Therefore, other wireless technologies such as Wi-Fi, ZigBee or Bluetooth could be utilized.

The research goal of this paper is to assess the tactical communication applications of in-X subnetworks. The assessment is done through a literature review of publicly available research on in-X subnetworks and tactical communication. The scope of tactical communication was broadened to include all types of digital data transmission used in military contexts.

The remainder of this paper is organized as follows: In Section II, the in-X subnetworking concept is introduced. Section III covers tactical communications and discusses the challenges of using in-X subnetworks in tactical communication. Section IV presents the idea of UAV swarms and their military applications, and how 6G in-X subnetworks could be utilized with them. Finally, conclusions are drawn in Section **??**.

II. In-X subnetwork

The 6G in-X subnetwork is a 6G wireless local subnetwork technology, where X is the entity where the subnetwork is installed e.g a vehicle. The in-X subnetwork aims to achieve performance metrics on par with wired connection, but not yet achievable by current technologies such as 5G, LTE, or Bluetooth. Simply put, the in-X subnetwork supports extreme communication requirements, either in terms of throughput, latency, and/or reliability. The aim is to achieve fraction of a millisecond latencies ($<100\,\mu$s), seven to nine nines reliability ($1-10^{-7\text{-}9}$), and data rates up to 100 GPS [3]. For reference, 5G Ultra-Reliable Low-Latency Communication is set to perform with $1-10^5$ reliability, and latency of 1 ms [6].

Due to the high performance of in-X subnetworks, they could be used to replace existing wired solutions using protocols like EtherCat [4]. Switching to wireless should provide benefits such as: reduction in weight, easier reconfiguration and maintenance, and more flexible deployment capability.

A. In-X subnetwork characteristics

The 6G in-X subnetwork is a low power and short range wireless cell. The subnetwork consists of an access point (AP) and connected devices. The connected devices are typically referred as sensors and actuators. Further, inside the subnetwork, the connected devices communicate with and through the AP, but not directly with eachother.

The networks are static, meaning that the connected devices are connected to a single AP. Though, the networks themselves can be mobile. The network is arranged to either a star or a tree topology, with one AP controlling the operations of the other devices connected to the subnetwork. Altough, multiple APs can be installed within a single subnetwork to accomodate potential primary AP faults [7]. As mentioned, the subnetwork is a short range wireless cell, meaning communication range up to 10 meters.

The in-X subnetwork is designed to operate both independendtly, and as a part of a larger network. While in coverage, the AP in the in-X subnetwork can communicate to the Wide area/enterprise network. More specifically, the AP can relay non-time critical data, such as Key Performance Indicators (KPIs), to be processed in the cloud. Thus, the in-X subnetworks are designed to support data flows with different characteristics in terms of latency. Figure 1 illustrates the structure and the data traffic flow of in-X subnetworks.

In the vision presented in [3], all aforementioned characteristics must be present to define a 6G in-X subnetwork, because the lack of just one would end up in a use case already tackled by other technologies. For example, dismissing the extreme communication requirements, then the remaining aspects define a wireless personal area network use case, with Wi-Fi, Bluetooth or ZigBee as possible candidates.

B. Proposed civil usecases of in-X subnetworks

Due to the performance of in-X subnetworks, many usecases for them have been proposed [3]:

- In-robot: motion control, force/torque control, position/proximity control,
- In-vehicle: engine control, electric power steering, ABS, electric park brakes, suspensions, ADAS sensors,
- In-body: heartbeat control, vital signs monitoring, insulin pumping, muscle haptic control,
- In-house: entertainment, gaming, training, education, healthcare (robotic-aided surgery).

These usecases have varying requirments in terms of throughput, latency, reliability, and other factors. As the in-X subnetworks are designed to provide wired connection level performance, many of the proposed usecases of in-X subnetworks are life-critical applications such as the aforementioned in-body or in-vehicle applications. In these usecases, the reliability of the network has to be ensured, but also in-body solutions have to energy efficient, as changing the batteries of the embedded devices might be difficult.

C. Spectrum aspects

Large spectrum use is needed to support the extreme communication requirements of in-X subnetworks. For example, a performance analysis [7] concluded that for an industrial scenario containing multiple possibly overlapping in-X subnetworks several hundreds of MHz worth of bandwidth is needed. This requirement indicates that the commonly used mobile communication spectrum below 6 GHz is not a viable solution as it is already over-crowded.

Due to the variety of different usecases and circumstances of in-X subnetworks, use of both unlicensed and licensed spectrum options and both lower and higher frequency ranges are proposed [3]. Depending on the movement, or the lack thereof, of the subnetworks, either unlicensed or licensed spectrum options are preferred. The use of licensed spectrum can be applied to static deployments with fixed or nomadic cells, such as cells installed in production modules or mobile roots in a factory. The mmWave 26-28 GHz band is a possible candidate. However, in mobile in-X subnetworks, licensed spectrum use might be problematic, since it would need roaming agreements among countries to ensure service continuity across borders.

Unlicensed frequency bands offer more flexible use across different regions, and thus are ideal for mobile cells that travel across regions. However, unlicensed spectrum can be overloaded with traffic, and thus the interference is high, which in turn can affect the reliability and/or throughput. Further, some regulations in the unlicensed spectrum can affect the latency negatively. Listen before talk procedure requires the devices to sense the channel, and possibly delay their transmission if the channel is already occupied [8]. While listen before talk procedure can be used delay tolerant applications, it clearly not compatible with strict latency requirements. Thus, the usage of these bands for time critical traffic would need new disruptive regulations to be introduced.

Alternative novel usage possibilities in the sub-terahertz bands (90-300 GHz) are considered for the in-X subnetworks. 6G research has focused on using the bands for extreme throughput short-range communications [9]. However, the bands suffer from poor perfomance in non-line-of-sight conditions, which are common for in-X subnetworks.

Deploying in-X subnetworks as ultra-wideband (UWB) underlay systems over spectra potentially allocated to licensed systems is also considered. UWB regulations allow for spectruym access in th 3.1-10.6 GHz region, with a maximum spectral density of -41.3 dBm/MHz and a constraint on minumum instanteneous bandwidth (e.g., 500 MHz according

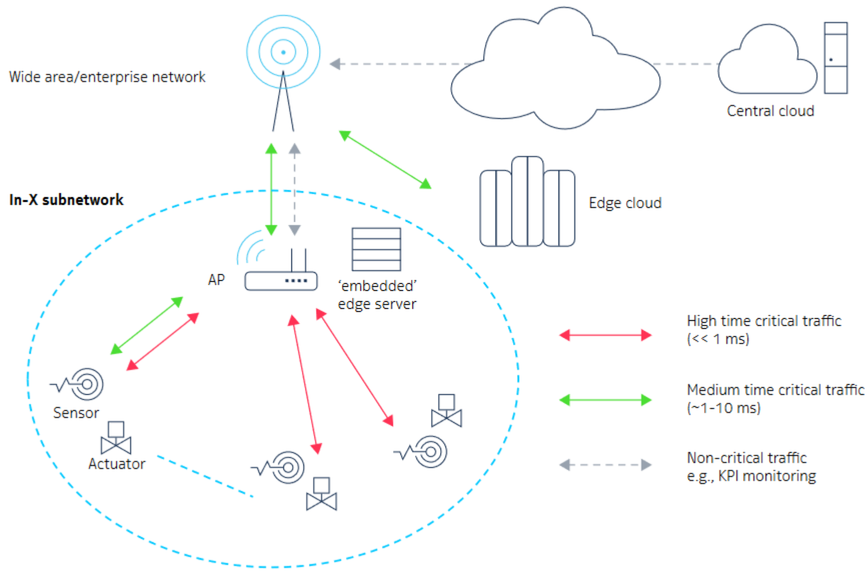

Fig. 1. Data traffic flow in and out of in-X subnetwork [3].

to the FCC) [10]. Though, UWB regulations can be an issue for dense deployments of in-X networks as the cumulative spectral density can be several orders of magnitude higher than the limits set by regulations. Finally, the in-X subnetworks are expected to be cognitive, and feature modern AI technologies. Thus, the spectrum sharing in terms of UWB and other similar techniques could be done more efficiently.

D. Interference management

The in-X subnetworks are designed to be able to operate in high interference scenarios. Further, as the cells are meant to service many life-critical usecases, they have to robust against interference of any type, whilst preferably maintaining high performance in terms of latency, throughput and/or reliability. Potential sources of interference include:

- dense deployments of in-X subnetworks,
- other users of the frequency bands if using unlicensed spectrum,
- jamming,
- impulsive noise caused by the presence of certain types of electro-mechanical devices, like microwave ovens or printers.

Interference management can operate on the frequency, time and spatial domains [11]. However, time domain interference management is not considered with in-X subnetworks that support low latency services; similarly spatial beamforming solutions may be ineffective given the limited AP and device form factor and therefore the expected low number of antennas. Hence, the interference management of in-X subnetworks should operate in the frequency domain, by dividing the available spectrum into several frequency chunks to be selected and assigned to the different subnetworks in a manner that minimizes the mutual interference.

While in coverage of a larger network, or some other central controller, the interference coordination should be centralized as it has been shown to outperform distributed schemes [12]. However, this type of interference management is only valid in licensed spectrum situations or when all the subnetworks can be managed by the same control element.

When out of coverage of central controller, distributed interference management should be utilized by in-X subnetworks. By sensing the different sub-bands the subnetworks are able to perform proactive decisions on the resources to be used. AI data driven methods could also be considered in this context [13].

Combining both centralized and distributed interference management approaches is also considered. The subnetworks in this case would alternate between the methods depending if they are in coverage of a central controller or not. However, the switch between the approaches should be done seamlessly without any service interruption. More discussion about distributed and centralized interference management of in-X subnetworks is given in [3], [14].

Additionally, communication requirement relaxation was proposed for scenarios were there is not sufficient available resources for supporting the service requirements of all devices on a subnetwork. For example, in a factory hall scenario involving many in-X subnetworks installed in robots or production modules, the communication cycle can be relaxed from e.g. 100 μ s to 1 ms or larger whenever the mutual interference levels are demmed to be to high to support the stricter latency requirement. [3]

On top of interference caused by other subnetworks, the subnetworks have to be robust against jamming and impulsive noise. In terms of jamming, resiliency against it includes being able to detect it and mitigate its effects. While in the reviewed literature the anti-jamming techniques used by in-

X subnetworks was not clearly specified, techniques such as physical layer methods (pilot/data transmission and pseudo-random blanking of frequency resources), and AI methods were brought forwards for detection. As for mitigation, conservative link adaptation, frequency hopping, transmit pattern scrambling and advanced MIMO schemes were floated around. [3]

III. Tactical communication

Tactical communications are military communications in which information, especially orders and military intelligence, is transmitted from one command, person, or place on the battlefield to another, particularly during combat [15]. However, in this paper the scope of tactical communication will be broadened to include everything in military use that is transmitting digital or analog data. Thus, this paper will, for example, evaluate the proposed civil usecases of in-X subnetworks for military use.

Tactical communication differs a lot from civilian communications. Civilian communications often rely heavily on established communication infrastructure, such as extensive optic fiber connections and wireless communication base stations. On the contrary, in tactical settings this sort of infrastructure is rarely available, as they are critical targets for enemies. More, EW threats are constant for wireless communications. The adversary might have capabilities to interfere or jam communications, or intercept them and possibly decoding the information or revealing your location by triangulation.

Tactical communication has two special requirements:

1) Tactical communication has to done covertly. This can mean covertness in frequency, time and spatial domains. In this paper, covertness is defined as covertness in the electromagnetic spectrum and not, for example, camouflage of communication equipment.
2) Tactical communication has to be robust against signal jamming.

These requirements are true for every type of tactical communication. However, wired communications emit little to no radiation, and thus are by nature covert and robust against jamming. Hence, these requirements mainly concern wireless communication. Altough, recent research into eavesdropping HDMI signal leaking from a HDMI cable suggests that wired solutions are not totally covert [16].

Wireless communication covertness primarily is achieved by avoiding omnidirectional transmission and using as little power as possible. On the other hand, robustness against signal jamming may involve using frequency hopping, transmit pattern scrambling, moving physically if the jamming is directed to a certain location.

A. *In-X subnetworks for tactical communication*

This paper argues that there is limited use of in-X subnetworks for tactical communication. The limited use possibilities is due to the design of in-X subnetworks, and their intented usecases not being compatible with military applications.

Firstly, many of the civil usecases of in-X subnetworks previously discussed in this paper provide little advantages in the military sector. In-robot, other industrial usecases, and in-house are not relevant to tactical communication. The in-vehicle usecase for military vehicles is hard to justify. Military vehicles are often armored and heavy, and thus the weight saving aspect of in-X subnetworks is neglible. More, this paper questions the funcionality of wireless subnetworks replacing engine control, steering or other functions of a military vehicle, due to challenging signal propogation environment caused by the armor. Further, there has to be some cabling to provide the electricity to the sensors and actuators of the subnetwork, or there has to be multiple batteries installed, which have to be charged or replaced increasing the need for constant maintenance of vehicle. Lastly, vehicles often are in the frontlines of battle, and thus any chance of jamming the controls of the vehicle could be detrimental for the operation.

However, the in-body subnetworks could have some use in combat environments. This paper envisions that in-body subnetworks could connect different types of sensors that could provide valuable data about the condition of the soldier. This could include information about the physical condition (hearbeat etc.) or equipment (ammunition etc.). Also, smart glasses with augmented reality capabilities could be connected to the in-body subnetwork used to show operation relevant information to the soldier. For example, information about the enemies and own troops locations.

Secondly, some design aspects of in-X subnetworks limit the use for military applications. Possibly the biggest limiting factor of in-X subnetworks that this paper recognizes is the operating range which is limited to approximately 10 meters [3]. This restriction essentially limits the use of the technology for relevant military usecases such as drone swarm communication [17] or any type of radio communication between operators. To be fair, the technology has not been envisioned for these types of deployments, and also range extension via multi-hop transmission has been mentioned. Additionally, if the range were to be streched near the limit of 10 meters, consequently the received power would be reduced and possibly make the system more susceptible to jamming or interference.

Third, some core functions of in-X subnetworks are irrelevant for tactical communication. The low latency, high reliability and throughput are the main qualities that set in-X subnetworks apart from other wireless technologies like Wi-Fi, Bluetooth or ZigBee. This paper argues that the extremely low latency of 100 μs nor throughput of many Gbps are not that crucial in many tactical communication applications.

IV. UAV swarms

UAVs are a major part of modern warfare [1]. UAVs have been found both effective in reconnaissance and assault. However, it is clear that a collection, swarm, of UAVs can achieve tasks that are impossible for a single UAV. To clarify, this paper defines an UAV swarm as a collection of UAVs that are controlled by a single operator, or that the swarm operates autonomously.

Many use cases have been found for UAV swarms [18]. However, this paper recognizes four different military applications of UAV swarms:

1) Intelligence, the swarm is able to sweep and survey areas faster than an individual UAV.
2) Assaul, the swarm can perform coordinated attacks, and thus inflict more damage than a single UAV.
3) Electronic warfare (EW), with EW equipment, for example Sirius Compact [19], the swarm can gather signal intelligence or perform jamming/anti-jamming measures.
4) Communication, the swarm is used to quicly establish ad hoc communication links between areas.

In the swarm different UAVs could have designated tasks and equipment. For example, a simple division of the UAVs to supporting and operating UAVs could be performed. The supporting UAVs could take care of the communication and be used for signal relay. Thus, they should be equipped with better communication equipment. On the other hand, the operational UAVs could carry operation specific equipment such as weapon systems, EW equipment, high definition cameras.

A. In-swarm: utilization of 6G in-X subnetworks for controlling a swarm of drones

This section presents how the 6G in-X subnetworks concept could be utilized as the intra-swarm communication method. As with the other use cases of in-X subnetworks, in the UAV swarm there would be a designated controller UAV, which is comparable to the AP in the normal 6G in-X subnetwork structure. The controller UAV is possibly connected to a ground control system or some other wide area network. The other UAVs would act as the sensors/actuators that the controller UAV controls, these UAVs would act as the operational ones.

In most cases, the swarm would adhere to the typical characteristics of in-X subnetworks. Thus, the non-controller UAVs would communicate with each other through the controller UAV. Also, the UAVs would be connected to a single controller UAV, and thus the network of UAVs would be arranged to a star topology. However, this paper envisions that for some UAV swarm applications there could exceptions especially to the topology of the UAV swarm. Further, atleast signal relay through UAVs should be supported in order to be able to perform all of the mentioned military use cases of UAV swarms.

Using 6G in-X subnetworks for intra-swarm communications provides many benefits. Firstly, controlment of the swarm could be done over the 6G mobile network, similarly how UAVs nowadays can be controlled over the internet. Secondly, the support of extreme communication could be leveraged depending on the use case of the swarm. For example, high throughput is needed for high definition video streaming, or low latency for communication applications. Finally, the diverse use of the spectrum and different interference management methods in 6G in-X subnetworks allow for dense deployments of UAVs [7], [14].

B. In-swarm communication link

This section presents on a high level the concept of using UAV swarm with in-X subnetworks to create ad hoc communication channels between areas. The main idea is that a the swarm of UAVs would form a line between two areas, and data would hop along the line of UAVs from end to end. The UAVs would form this line, or other topology, by autonomously organizing themselves and flying to their respective spots. These spots could be on buildings, on the ground, or even tree branches [20]. However, neighboring UAVs should have a line-of-sight connection in order to have beamforming connection between them, this means that the distance between neighboring UAVs depends on the environment. The UAVs should communicate only with their immediate neighbors, but also be aware of the next-hop neighbors in case of their immediate neighbors would fail. Similar ideas for emergency networks in disasters have been presented in literature [21].

There could be a reserve of UAVs that could fly in and replace other UAVs that need to fly back to recharge or to be maintained. Additionally, the in-swarm communication link should have some capabilities to detect if any of the UAVs forming the line is compromised or detected. More, then the UAVs should be able to react accordingly by, for example, disenganing or reforming the communication link.

The motivation for the in-swarm communication link is encouraging. Firstly, the establishment of the link would be fast and autonomous, and thus could be constructed over areas where it is risky to deploy troops, such as minefields or contested areas. More, due to the autonomity, the forming of the communication link would not tie any man power. Further, the connected areas do not have be in line of sight of eachother. Lastly, in-swarm communication links could be used in conjuction with other common communication link methods such as wireless communication link masts or fiber/wired connections in order to solve their shortcomings such as line-of-sight dependency or unsuitable terrain for wires.

However, the this paper recognizes some limitations in the in-swarm communication link concept. One major limiting factor is the battery life. The flight times of battery powered UAVs range from 30 minutes up to 2 hours [22] depending on, for example, the payload and if it is fixed-wing or not. The UAVs should be able to fly into their respective spots, be able to operate the communication link for some while, and then have enough power to fly back. This restricts the range of whole communication link as the distance is larger more battery life is spent on flying in and out of the formation. Also, as the distance and amount of hops grow in the communication link so does the overall end-to-end latency, and similarly the end-to-end reliability worsens. Additionally, one possible problem is GPS-denied environments, because in order to able to autonomously organize the UAV topology the UAVs must have accurate location data.

C. Modification of in-X subnetworks for in-swarm applications and further research

This section discusses the needed modifications of the in-X subnetworks for the presented in-swarm applications and identifies further research directions. Most importantly, the maximum range inside the in-X subnetworks should far exceed 10 meters. Atleast, the communication, EW, and intelligence in-swarm applications require up to 100 meters of maximum range for them to be viable. For assault purposes the shorter range could be acceptable. Secondly, the subnetworks should support non-tree or star topologies. For example, the communication link applications would require line-like topologies.

Finally, beamforming in UAV-to-UAV communication. Beamforming would provide many benefits in in-swarm applications. It would reduce signal emissions making the communication more covert, and it would act as spatial interference management tool, and thus allow for more numerous deployments of UAVs in the swarm.

Further research should be conducted to determine the viability of in-X subnetworks for in-swarm applications. One of the biggest factors that should be researched is the operation time of the swarm in different use cases. In general, it should be determined how much power does the intra-swarm communications require power especially if beamforming is used. Also, it is necessary to map how much power would the operation equipment such as cameras and computing resources use. These factors are especially crucial for the in-swarm communication link use case, where the UAVs would be grounded and used for communication for extended periods of time.

Other research questions include: swarm navigation in GPS-denied environments, reaction and recovery of losing a controller UAV, and benefits of 6G in-X subnetworks over existing technologies such as 5G Sidelink, Wi-Fi, Bluetooth. The reaction and subsequent handover off controls to an another UAV in case of losing the controller UAV in the swarm should be as seamless as possible.

V. CONCLUSIONS

This paper presented the high level concept of in-swarm: using 6G in-X subnetworks for controlling a swarm of UAVs. The 6G in-X subnetworks are envisioned as low-power and short-range wireless subnetworks, where the X stands for the entity where the subnetwork is deployed. The in-X subnetworks are a projected key technology in 6G. Further the motivation behind in-X subnetworks is to provide wired connection level performance in short range subnetworks, while avoiding drawbacks associated with setting up wiring such as high cost, limited deployment flexibility, and weight.

However, due to the short range, unrelated civil use cases and benefits, and limited topology options, in-X subnetworks have limited use in tactical communication. Still, this paper identified internal communications and controls of UAV swarms as a possible tactical communication use case for in-X subnetworks. Though, some modifications to the original concept of in-X subnetworks should be made, especially the range of the intra-subnetwork communication should far exceed 10 meters.

This paper identified four major tactical use cases for the UAV swarms: intelligence, assault, electronic warfare, and communication. More in-depth view was given to the communication use case, where the UAV swarm is used to create an ad hoc communication link between areas. The paper envisions that UAV swarm communication links could be created autonomously with no human involvement, and thus allowing connections to be made over hazardous or otherwise inadequate areas. The paper gave futher research questions that are crucial for the in-swarm concept, such as the operation time in terms of battery life, navigation in GPS-denied environments, and utilization of existing wireless technologies.

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